

IN THE UNITED STATES PATENT OFFICE

--A DIRECT ELECTRODYNAMIC LINEAR DRIVE--

BACKGROUND OF THE INVENTION

5 The invention relates to a direct electrodynamic  
linear drive comprising a drive coil system made up of a  
plurality of adjacently arranged coils, said system being  
adapted to be operated by a switched exciting voltage, and  
a plurality of adjacently arranged permanent magnets,  
10 means being provided for relatively moving on the one hand  
permanent magnets and the drive coil system on the other  
hand.

THE PRIOR ART.

15 In the case of a previously proposed linear direct  
drive disclosed in the German patent publication  
19,748,647 A1 the coils are arranged on the inner side of  
a ferromagnetic tube, whereas the permanent magnets are  
able to be moved within the drive coil system. It is more  
especially in the case of elongated arrangements that this  
20 leads to substantial bearing problems for the permanent  
magnets able to be moved within the coils and a force  
transmitting element must be fixed to the magnets.

SHORT SUMMARY OF THE INVENTION

25 One object of the invention is to create an  
electrodynamic linear drive, in the case of which the  
armature may be simply and reliably supported by bearing  
means even in the case of an extremely long drive.

30 This object is to be attained with a direct  
electrodynamic linear drive comprising a drive coil system  
composed of coils arranged in a row alongside each other  
on an elongated ferromagnetic core, which coil system is  
able to be supplied with a switched exciting voltage, and

a ferromagnetic tube fitting around the drive coil system, a plurality of permanent magnets being arranged on the inner side of the said tube in a row alongside each other in the longitudinal direction of the tube, the core being provided with drive coil system and designed as a stator and the tube provided with the permanent magnets being designed as an armature.

The ferromagnetic tube surrounding and holding the drive coil system has a multiple function and serves on the one hand as guide element for the armature and on the other hand as a magnetic return member for containing the magnetic field. Such a ferromagnetic tube can be reliably and exactly guided on the outer side by longitudinal guide bearings readily for longitudinal movement, whereas the drive coil system may be fixed in the interior of the tube or, respectively, of the permanent magnets in a stationary manner.

The measures recited in the claims represent advantageous further developments and improvements of the novel direct linear drive specified.

It is an advantage for the tube to be slidably mounted in a longitudinal duct in a housing, the drive coil system extending into the longitudinal duct from one side. This means that a direct linear drive can be manufactured with an extremely small housing cross section and a great longitudinal extent.

In order to ensure that the drive coil systems is centered in the ferromagnetic tube with relatively small distances from the permanent magnets a non-ferromagnetic guide tube extends along radial inner faces of the permanent magnets, at least one support element being arranged additionally on the elongated core for sliding or rolling along the inner face of the guide tube.

The radially magnetized permanent magnets fit about the drive coil system and are more particularly made up of



inductance fractions of the differential choke system and therefrom finding the position. Such an integrated displacement or travel measuring system is of independent significance as a subcombination and may also be employed in other direct linear drives, in the case of which a permanent magnet arrangement is able to be shifted in relation to the drive coil system and the latter comprises coils in a row on a ferromagnetic core.

Further advantageous developments and convenient forms of the invention will be understood from the following detailed descriptive disclosure of embodiments thereof in conjunction with the accompanying drawings.

#### LIST OF THE SEVERAL VIEWS OF THE FIGURES.

Figure 1 is a diagrammatic section-like overall view of an electrodynamic direct linear drive as one embodiment of the invention.

Figure 2 shows part of a similar arrangement in the case of which the axial length of the drive coil system is larger than that of the permanent magnet arrangement.

Figure 3 is a representation to explain the circuit connections of the coil parts of the drive coil system.

Figure 4 shows a known evaluating or processing circuit for a displacement or travel measuring system in the form of a differential choke system.

Figure 5 is a signal graph for explaining the workings of the system.

DETAILED ACCOUNT OF WORKING EMBODIMENTS OF THE INVENTION.

In the case of the embodiment of the invention depicted in figure 1 in the form of an electrodynamic direct linear drive a housing 10 has a blind hole, in which a ferromagnetic tube 11 is guided by means of bearing units 12 for longitudinal motion. The bearing units 12 engage the outer face of the tube 11 and are in the form of plain or anti-friction bearing arrangements. Same fit as keys in longitudinal grooves, not illustrated in detail, in the ferromagnetic tube 11 to prevent relative rotation. As an alternative to this it is possible for the ferromagnetic tube 11 to have an oval-like or a prismatic cross section instead of a round one, such cross section then in itself preventing relative rotation.

Radially or diametrically magnetized permanent magnet rings composed of magnet segments or magnet shells, which themselves are radially or diametrically magnetized, are placed in the tube 11 acting as a guide tube, such rings being in the following termed magnets 13, which are so arranged and so fixed to the bore of the tube 11 that in the axial direction there is an alternating field sequence with a radial alignment of the field. The tube 11, which for example is in the form of a steel tube, constitutes the armature of the direct linear drive and serves to receive the magnets 13 as a magnet return means for containing the magnetic field and as a guide tube.

The stator arranged within the armature essentially comprises a ferromagnetic core 14, which may be in the form of a steel or iron core of round solid or tube material, on which a cylindrically wound drive coil system

15 is provided. The core 14 provided with the drive coil system 15 is here fixed to one end on the inner side of the housing 10 and extends out into the blind hole or, respectively, the ferromagnetic tube 11 from the inner side of the housing 10. The inner side of the magnets 13 is provided or lined with a non-magnetic, thin-walled lining tube 16, whose bore serves as a sliding face for a support element 17, which is mounted on the free end of the core 14 and itself is designed in the form of a plain or anti-friction bearing. By means of this support element 17 the core 14 and the drive's coil system 15 are reliably guided within the magnets 13 with a minimum gap therebetween.

If the ferromagnetic tube 11 has a non-round cross section then the components contained in it will naturally be suitably shaped to comply.

The end protruding from the housing 10 of the armature or, respectively, tube 11 is connected at its end by way of a connecting element 18 with a rod 19, which extends in parallelism to the tube 11 into a hole in the housing 10 and is guided for motion therein. This rod 19 extends through a detecting means 20, with the aid of which the respective position of the armature may be detected, for example electrically. Such detecting means 20 are known in a large number of different types so that a more detailed description thereof is unnecessary. Furthermore, such rod 19 and/or the tube 11, directly cooperating with the sensor means 21 extending in parallelism thereto, constitutes a displacement measuring system for finding or ascertaining the respective position of the armature. As will be explained at greater length later, it is possible for the sensor means 21 and the corresponding displacement measuring system to be dispensed with by connecting up the drive coil system 15

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5 e. the drive coil system 25 depicted there is longer than  
the permanent magnet arrangement consisting of four  
magnets 26, and longer than the corresponding armature. A  
ferromagnetic tube 27 is correspondingly shortened which  
receives the magnets 26 and an inner non magnetic thin-  
walled tube 28 is also shortened. In this arrangement the  
magnet volume is optimally used, the partly unused coil  
regions producing unnecessary heat.. On the other hand  
the armature's mass in such an arrangement is reduced,  
something which improves the dynamic properties. In  
figure 2 the magnetic field lines are diagrammatically  
represented in chained lines and the direction of winding  
of the coil parts of the drive coil system 15 are  
indicated using conventional symbols.

15 As a source of power for the electrodynamic direct  
linear drive only one power supply connection (not  
illustrated) and only one control connection with an  
external central arrangement are required, such  
connections being for example in the form of a field bus  
or a binary bus. All initializing and regulation  
operations are implemented by the integrated electronic  
circuitry, something which renders the unit extremely easy  
to handle and minimizes the amount of wiring necessary.

25 The function of the integrated displacement measuring  
means is based not, like the prior art of the type  
initially mentioned, on the measurement of moving, highly  
permeable cores in the differential choke systems, but on  
the measurement of changes in inductance caused by  
saturation phenomena, which are shifted by the movement of  
the armature, which owing to the magnets 13 is permanently  
magnetic, and thus cause changes in inductance along the  
displacement, which changes may then for instance be  
detected by way of methods indicated in the prior art  
cited.



Figure 2 shows the principal field configuration of the linear drive with all significant components. Owing to the containment of the field by the core 14 induction changes of different intensity result. Such changes may be split up into regions of weak induction, that is to say also of weak magnetic saturation in the iron, and into regions of strong induction, that is to say of strong magnetic saturation in the iron. From the relationship between induction with the known BH magnetization line of the iron material employed (B meaning induction and H meaning field strength) which may also be represented in a  $\mu B$  characteristic or function, we obtain a certain variation in permeability ( $\mu$ ) in the iron core in the axial direction.

The variation in permeability is set by the permanent magnets of the armature and accordingly the position of the armature. This variation in permeability may be employed electrically for detecting the position by way of the coil inductance of the drive coil system 25. The coil inductance is dependent on the magnetic resistance and the number of winding turns. The magnetic resistance is for its part not only dependent on the volume of the material or the area and the magnetic length of the field segments (constant in the working example) but also on the permeability.

In order to be able to now use the principle of integrated displacement measurement, it is necessary for the drive coil system 25 and, respectively, 15 to be so designed that a differential choke system is produced. This will be explained with reference to figure 3 and two coil parts 29 and 30 of the drive coil system 25 and, respectively, 15 used in the working embodiment of the invention. In the case of this two strand coil system employed in the working example, in which in the axial direction every second coil part 29 and 30 as connected in

series leads to one strand, these coil parts 29 and 30 are again divided up into coil regions 29a and 29b and also respectively 30a and 30b and so wound that there is a strand divided into two parts in which every first region part 29a of a coil part 29 is placed in circuit with every further first coil region 30a of a coil part 30 of the same strand in series to produce a half strand (the supply strand) and every second coil region 29a and 29b of the coil part 29 and 30 is placed in series with one second half strand (the return strand). The connection point between the supply and return strands is also made available as a center tap terminal 31 between the end terminals 32 and 33.

Each further strand is placed in circuit in this same manner. Since now the changing variation in permeability in the respective coils of a half strand is geometrically offset on movement of the armature therethrough, in the respective strand parts (which owing to the connection in series may respectively be looked upon as single inductance) sinusoidal inductance variations will result which are offset in relation to each other in accordance with the distance apart of the coil parts. Owing to the particular coil circuit arrangement of the half strands there is now a differential choke system in accordance with figure 4, which comprises the two inductance parts  $L_1$  and  $L_2$ , in the case of which, unlike prior known designs, there is no core motion. In this differential choke system it is now possible, using the inductance measuring method represented in figure 4 and previously proposed in the cited prior art, to ascertain the ratio between the two inductance fractions  $L_1$  and  $L_2$  of the half strands of a complete strand.

By now plotting the inductance changes of both complete strands against displacement, we will have the signal curves indicated in figure 5. The idealized true

sine curve will correspond to the variations in induction in the iron core (left hand scale) and the asymmetrical curves will correspond to the computed induction variations in the two strands of the motor windings on full movement of the armature, which represent the displacement signals (right hand scale) to be evaluated or processed. These curves are asymmetrical, since magnetization characteristics of the material utilized are non-linear. Measurement of the displacement is now performed on the one hand by counting the respective periods and interpolation of the analog intermediate values so that we have a relative displacement measuring system with absolute displacement interpolation in the respective segments.

For detection of the position values on the basis of the signal variations use is made of the known circuit illustrated in figure 4. As already mentioned the two half strands 34 and 35 of the complete strand of the drive coil system 25 and, respectively, 25 are connected in series. Operation takes place by the application of a pulse width modulated square pulse voltage  $U_{PWM}$ , which is generated in a position or path regulator 36 designed in the form of microprocessor and by way of a driver stage 37 to the half strands 34 and 35.

For the measurement of the inductance changes the voltage drops  $U_{m1}$  and  $U_{m2}$  across the half strands 34 and 25 are decoupled separately using a respective measuring or precision amplifier 38 and 39 and as regards the signal level adapted to the following electronic evaluating circuit. Accordingly representations of the voltage parts across strands 34 and 35 will be present at the outputs of the measuring amplifiers 38 and 39. By electronic differentiation in the following differentiating stage 40 and 41 of the voltage signals at the output of the measuring amplifiers 38 and 39 respectively shortly after

switching over the pulse width modulated setting signal it is possible for the inductance ratio of the two half strands 34 and 35 to be ascertained which are switched at the pulse frequency. By subtraction of the rates of increase of the voltages for the two half strands 34 and 35 by means of a subtraction stage 42 for the accuracy of the detection of the inductance ratio may be increased by elimination of interfering DC factors. If the detection of the inductance ratio is always performed at the same point in time after switching over the setting signal and intermediately stored in the working example in a sample and hold means 43 and 44, there will accordingly be a displacement-dependent quasi-continuous DC signal at the output of the subtraction stage 42. In extensive parts thereof this signal will be linearly dependent on the armature position and consequently corresponds to the respective true position value  $x_{1st}$  of the armature.

The signal  $x_{1st}$  present at the output of the subtraction stage 42 is now employed for regulation by coupling such signal with a target position value  $x_{soll}$  and deriving from this the control signal. Accordingly using the arrangement described it is possible to perform the displacement and also a displacement signal.

The above described displacement measuring system is not only suitable for electrodynamic direct linear drives in accordance with the working examples but also for other electrodynamic direct linear drive, which differ in design from the working embodiments herein.